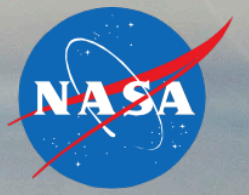
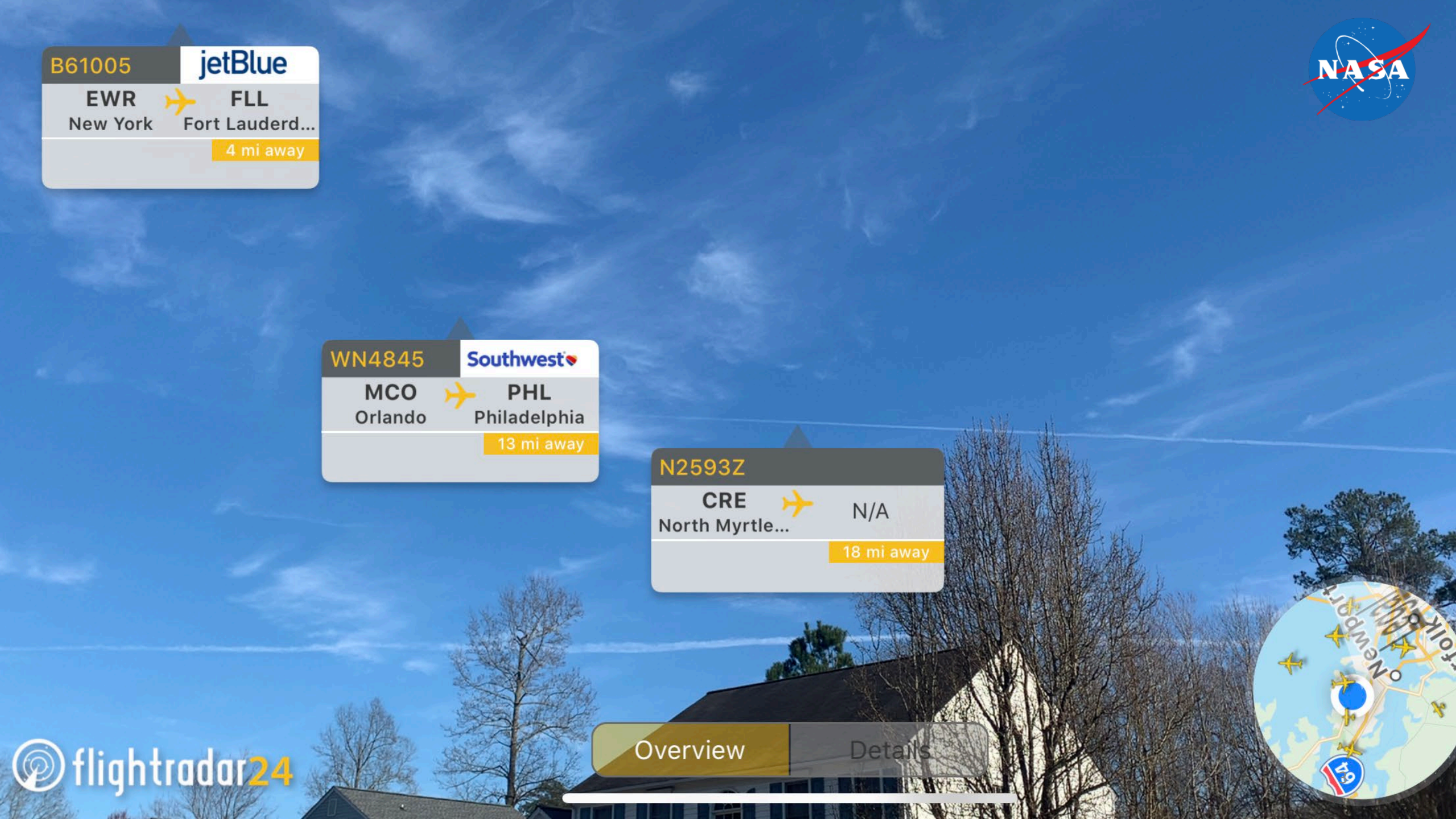
National Aeronautics and Space Administration



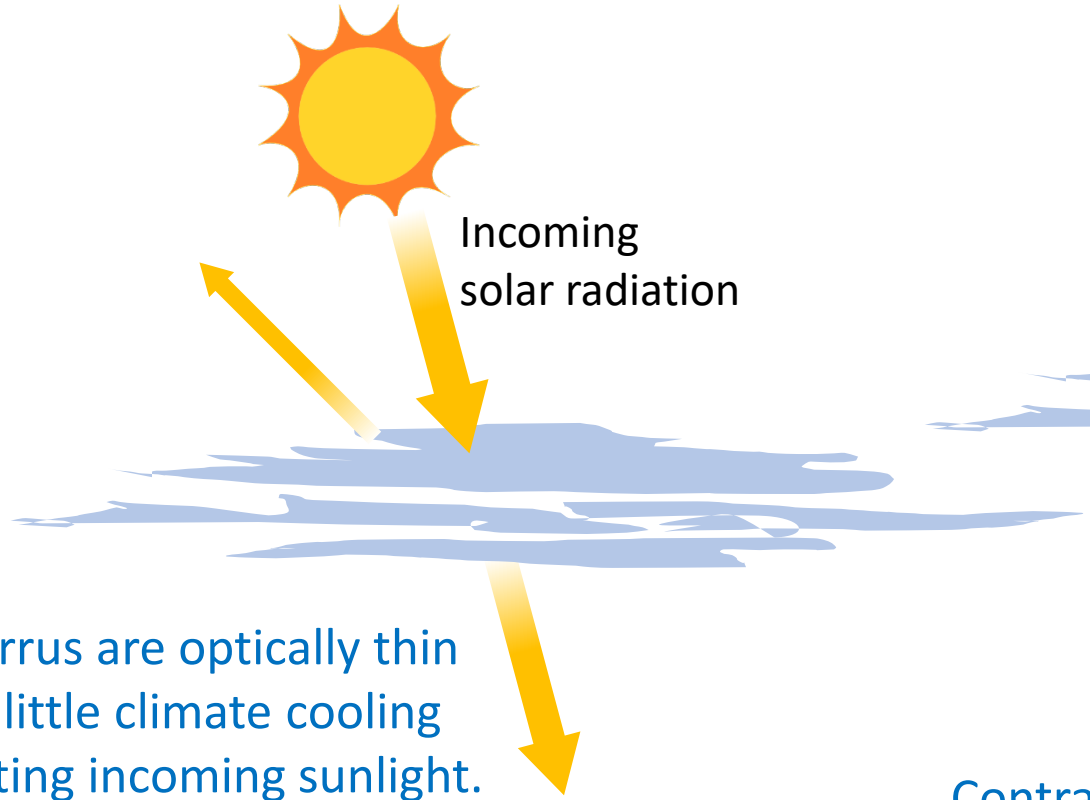
Sustainable Aviation Fuels Reduce Aviation Impacts on Air Quality, Contrails, and Climate

Richard H. Moore
NASA Langley Research Center, Hampton, VA 23681
richard.h.moore@nasa.gov; Twitter: @richardhmoore

ARMD Technical Seminar
14 March 2023


B61005
jetBlue
EWR
New York
FLL
Fort Lauderd...
4 mi away
WN4845
Southwest
MCO
Orlando
PHL
Philadelphia
13 mi away
N2593Z
CRE
North Myrtle...
N/A
18 mi away
NASA
flightradar24
Overview
Details

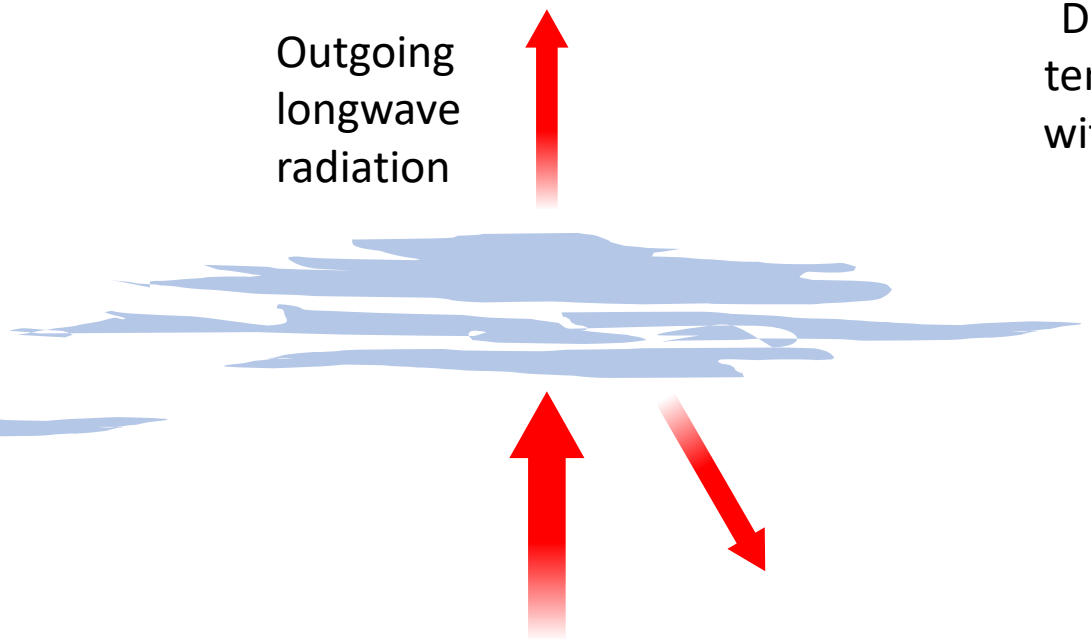
Contrail-cirrus clouds warm Earth's climate (based on physics), but the magnitude of the net climate effect is where there are large uncertainties!



Incoming solar radiation

Contrail-cirrus are optically thin and have little climate cooling from reflecting incoming sunlight. Might have a slight impact (~10%) on photovoltaics.

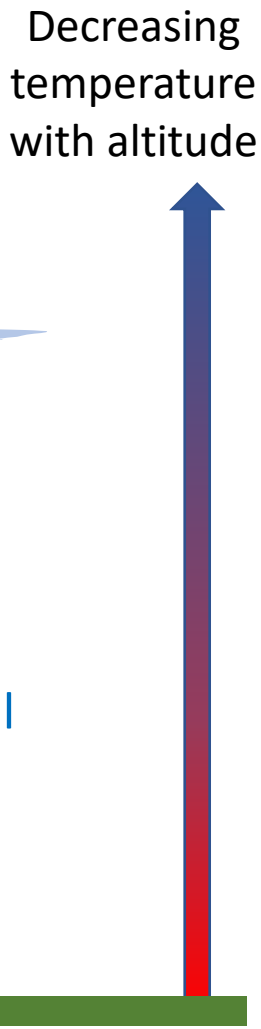
Gruber et al., *Atmos. Chem. Phys.*, 2018



Outgoing longwave radiation

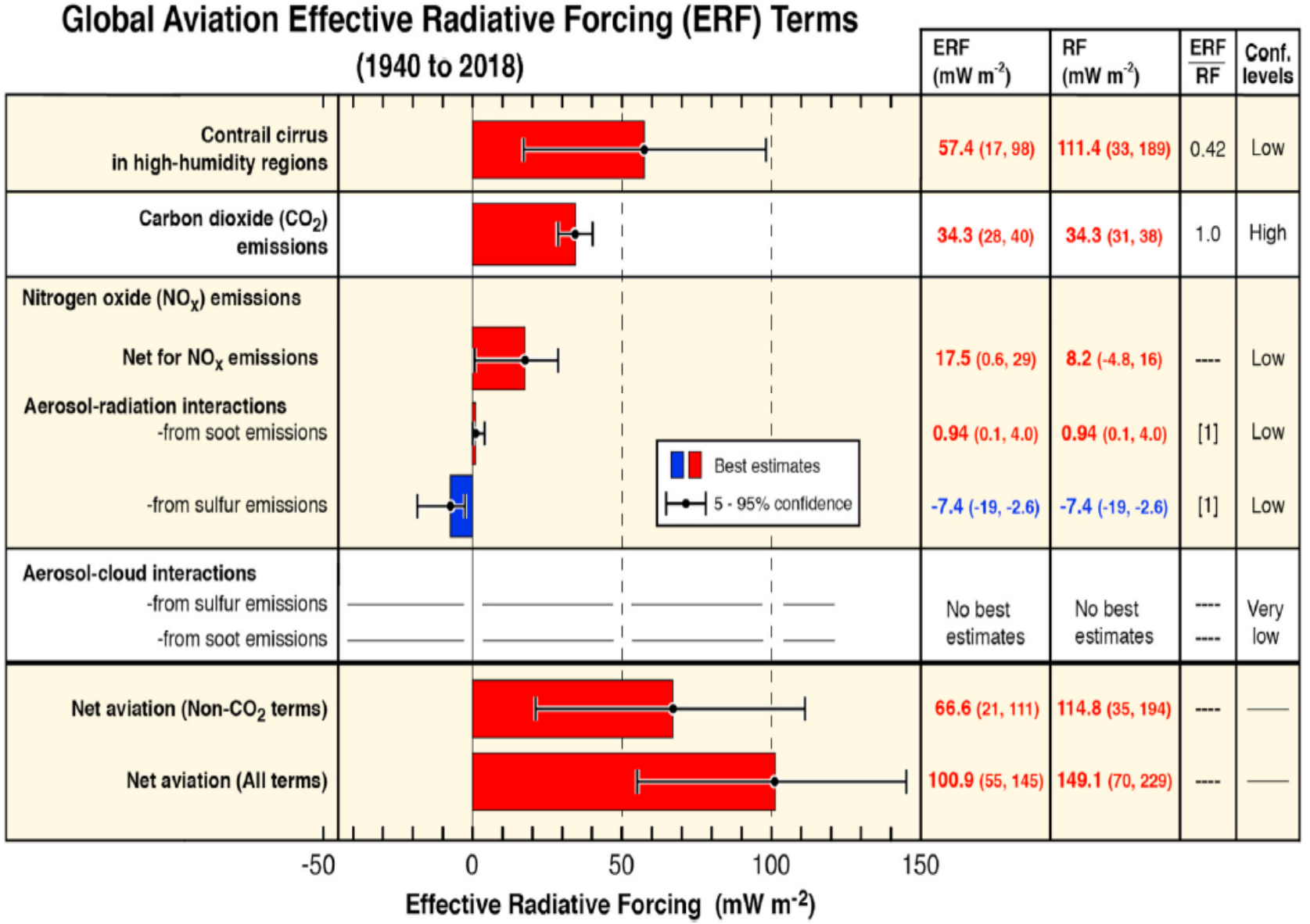
Contrail-cirrus absorb Earth's outgoing thermal energy and re-emit it at a colder brightness temperature, which results in a large, net warming effect on climate!

https://en.wikipedia.org/wiki/Stefan-Boltzmann_law



Decreasing temperature with altitude

Recent Assessment Emphasizes the Larger Climate Warming From non-CO2 Aviation Impacts (i.e., Contrails)

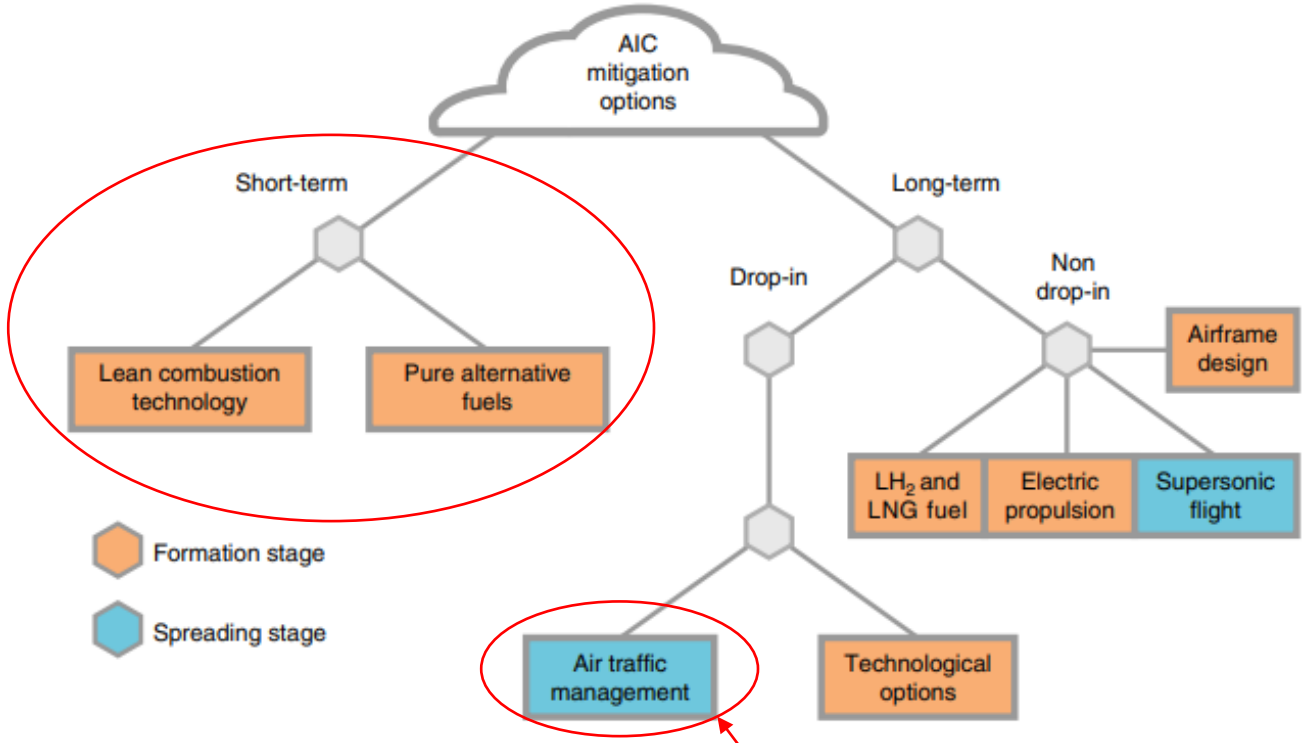


	ERF (mW m^{-2})	RF (mW m^{-2})	ERF/RF	Conf. levels
Contrail cirrus in high-humidity regions	57.4 (17, 98)	111.4 (33, 189)	0.42	Low
Carbon dioxide (CO_2) emissions	34.3 (28, 40)	34.3 (31, 38)	1.0	High
Nitrogen oxide (NO_x) emissions				
Net for NO_x emissions	17.5 (0.6, 29)	8.2 (-4.8, 16)	----	Low
Aerosol-radiation interactions				
-from soot emissions	0.94 (0.1, 4.0)	0.94 (0.1, 4.0)	[1]	Low
-from sulfur emissions	-7.4 (-19, -2.6)	-7.4 (-19, -2.6)	[1]	Low
Aerosol-cloud interactions				
-from sulfur emissions	No best estimates	No best estimates	----	Very low
-from soot emissions			----	
Net aviation (Non-CO_2 terms)	66.6 (21, 111)	114.8 (35, 194)	----	——
Net aviation (All terms)	100.9 (55, 145)	149.1 (70, 229)	----	——

Lee et al. (2021) "The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018" *Atmospheric Environment*, https://doi.org/10.1016/j.atmosenv.2020.117834

A Number of Pathways For Mitigating Aviation-Induced Cloudiness (AIC)

- Karcher (2018) also reviews potential pathways for mitigating/reducing contrail cirrus cloud production in the near-to-mid-term.
- Sustainable Aviation Fuels (SAFs) hold great promise for soot particle emissions reductions, and hence, contrails.
- In addition, new, low-emitting lean combustion engines like the CFM LEAP-1B engines on the Boeing 737-MAXs also hold great promise for reducing soot and contrails.



Options to mitigate the climate impact of aircraft-induced cloudiness. Fig. from Karcher, *Nature Communications*, 2018.

It's Not Just A Climate Story – Aviation Emissions Impact Air Quality of Communities Near Airports

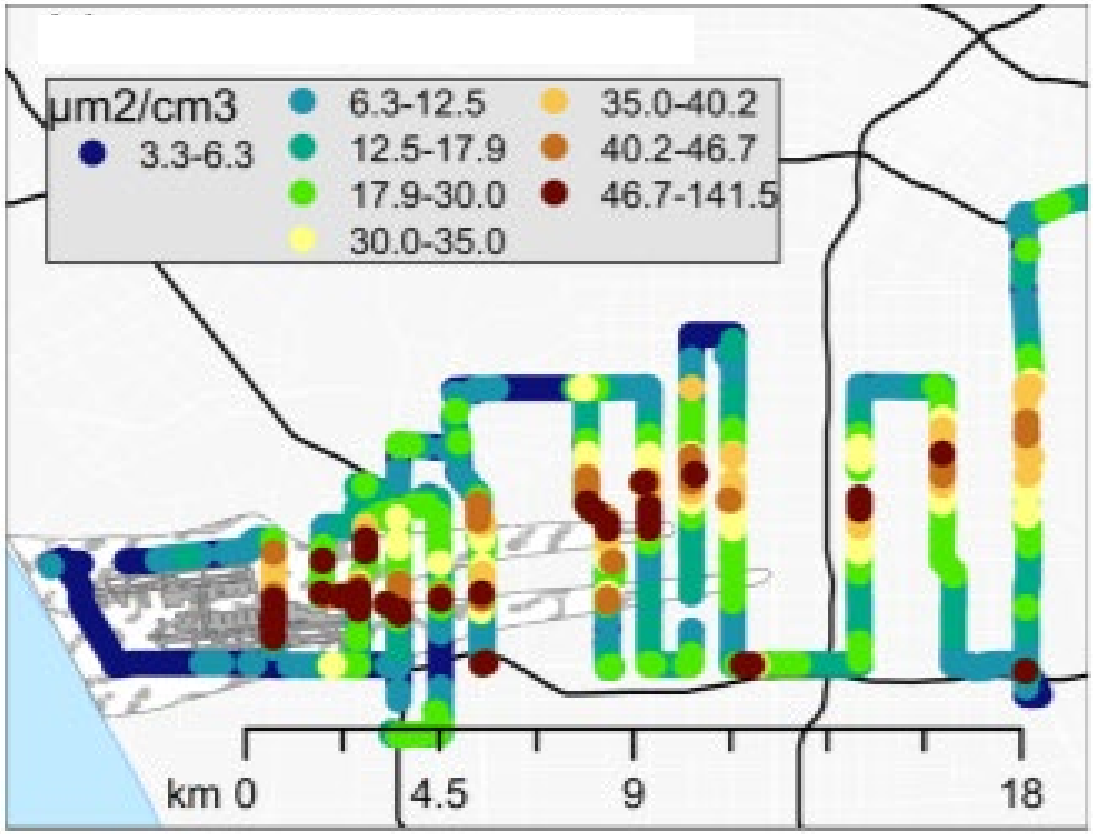
- Emissions relevant to air quality occur over the landing and take-off (LTO) cycle, comprising:
  - Idle
  - Taxi
  - Take-off
  - Climb out (0-3,000 feet)
  - Landing (0-3,000 feet)

- The International Civil Aviation Organization (ICAO) tabulates emissions parameters for NO_X, CO, hydrocarbons, particle "smoke #", **and (as of Dec. 2020) mass & number!**

- Need to quantify emissions under real-world conditions

- Particle emissions reductions from burning SAFs and from newer lean-burn combustion engines improve air quality!

Aerosol surface area measured 0-18 km downwind of LAX



Hudda and Fruin, *Environ. Sci. Technol.*, 2016

Sustainable Aviation Fuels As A Cornerstone of the Biden Administration Climate-Friendly Policy

Biden administration sets goal of replacing all jet fuel with sustainable alternatives by 2050

The administration says boosting the use of fuels made from waste or plants could cut emissions from flying 20 percent by the end of the decade

Listen to article 3 min

Aeronautics

Sep 9, 2021

RELEASE 21-118

NASA Innovations Will Help US Meet Sustainable Aviation Goals

NASA will demonstrate high-risk, high-reward technology advancements critical for U.S. aerospace manufacturers to bring to mark
cost-effective, and sustainable products and services demanded by airlines and customers.
Credits: Vehicle image created by Scott Anders, Rich Wahls and Lillian Gipson; Forest Imagery franckreporter, E+, Gettyl

NASA Administrator Bill Nelson joined federal government and industry leaders Thursday at a White H
highlighting sustainable aviation and the administration's focus on medium- and long-term goals to con
climate change.

THE WHITE HOUSE

BRIEFING ROOM

FACT SHEET: Biden Administration Advances the Future of Sustainable Fuels in American Aviation

SEPTEMBER 09, 2021 • STATEMENTS AND RELEASES

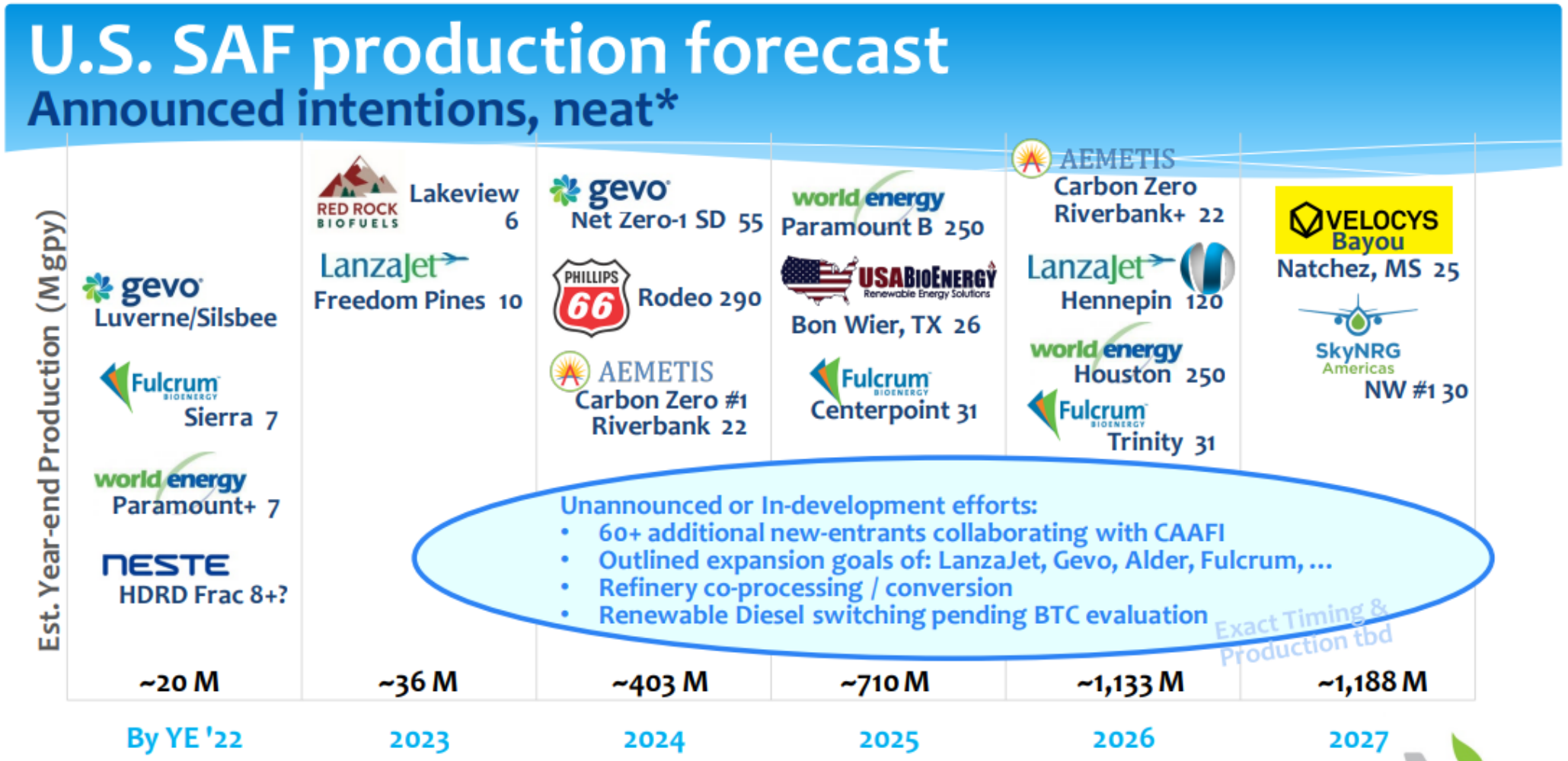
New Actions Aim to Produce Three Billion Gallons of Sustainable Fuel, Reduce Aviation Emissions by 20% by 2030, and Grow Good-Paying, Union Jobs

Today, President Biden is taking steps to coordinate leadership and innovation across the federal government, aircraft manufacturers, airlines, fuel producers, airports, and non-governmental organizations to advance the use of cleaner and more sustainable fuels in American aviation. These steps will help make progress toward our climate

https://www.whitehouse.gov/briefing-room/statements-releases/2021/09/09/fact-sheet-biden-administration-advances-the-future-of-sustainable-fuels-in-american-aviation/

https://www.nasa.gov/press-release/nasa-innovations-will-help-us-meet-sustainable-aviation-goals

It's Still Early Days For SAF Production
(Global Jet Fuel Consumption ~ 100 B gal./yr. Pre-Covid)



NASA Emissions Research Improves Understanding of Fuel Chemistry & Emissions; Motivates and Advances SAFs

SNIF, SUCCESS Flight Tests
Concerns about high-sulfur content of petroleum-based jet fuels motivate studies linking fuel chemistry to volatile particles and contrails.

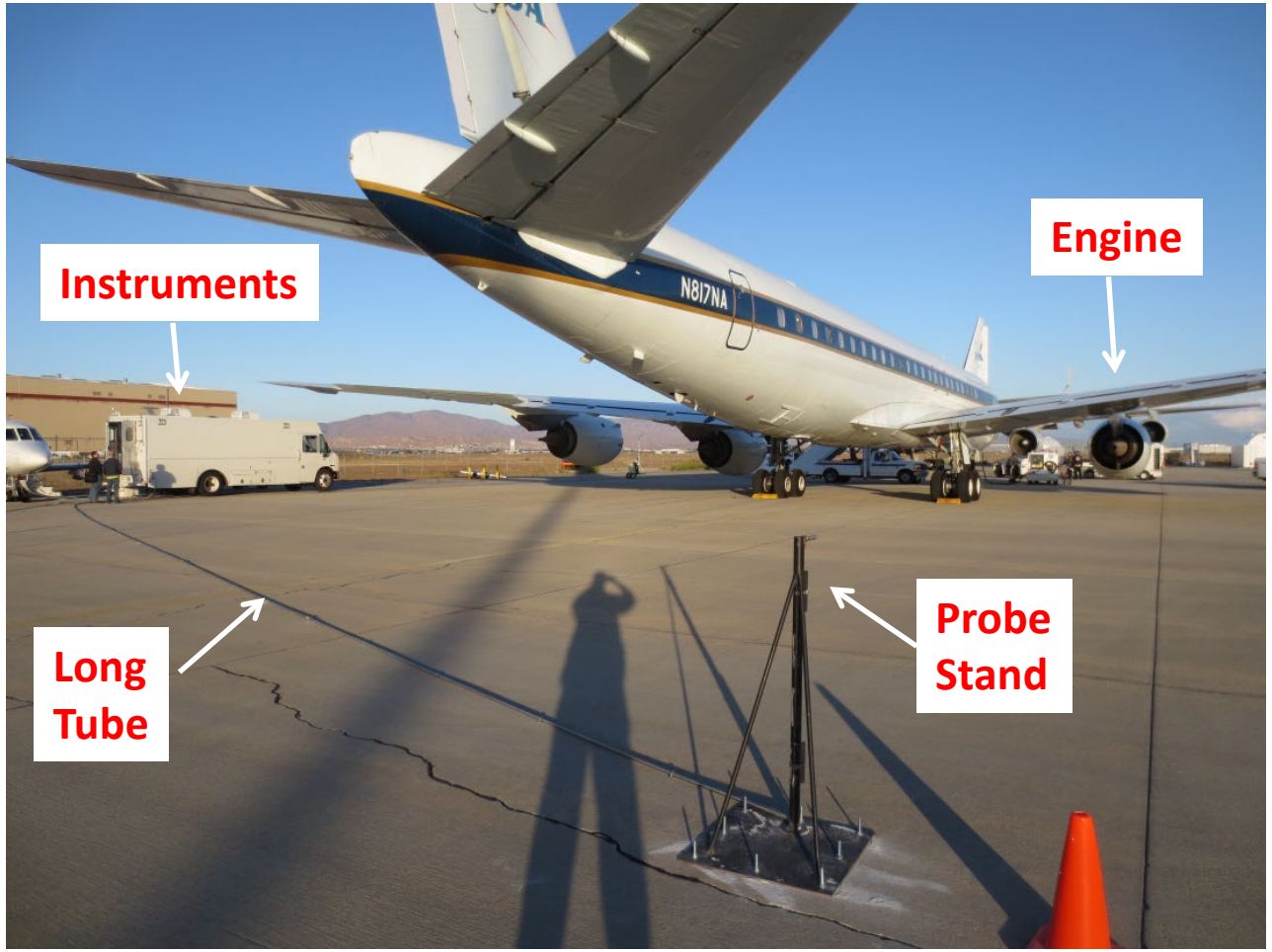
ACCESS, ND-MAX Flight Tests
First, in-flight, chase plane studies with SAF blends show that particle emissions reductions observed during **AAFEX** also translate into lower emissions and fewer contrail ice crystals at cruise altitudes.

1990s | 2000s | 2010s | 2020s

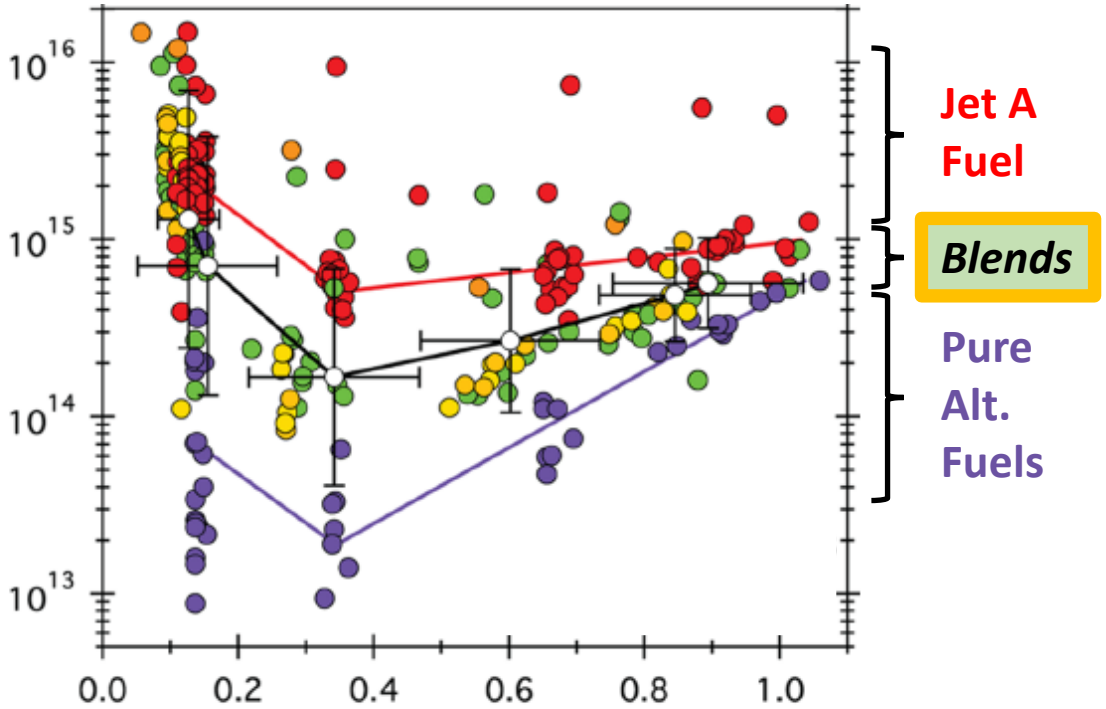
APEX, AAFEX Ground Tests
First ground tests with SAFs show large soot particle emissions reductions. Tests also inform SAE E-31 regulatory methodology recommendations for ICAO WG3.

Boeing ecoDemonstrator Ground and Flight Tests
First ground & flight tests with pure SAFs + lean-burn engines will assess “best currently possible” particle & contrail reductions.

APEX, AAFEX, ACCESS Ground Tests With NASA DC-8 Quantify Alternative Fuels Emissions Reductions



Number of non-volatile particles emitted per kilogram of fuel burn



Anderson, B.E. et al., NASA/TM-2011-217059, 2011
Beyersdorf A.J. et al., *Atmos. Chem. Phys.*, 2014
Moore, R.H. et al., *Energy & Fuels*, 2015

However, Cruise Conditions Are Very Different From The Ground, Which Necessitates In-Flight Testing

2013-2014

ACCESS

- Flight test series conducted at Edward AFB complex
- Falcons are slow, but can sample exhaust up close
- Two fuels: Jet A and 50:50 Jet A and Biofuel Blend
- Corresponding ground test to link to past studies

2018

ND-MAX ECLIF

- Flight test series conducted in German air space
- DC-8 is fast, but was required to sample > 5 km in trail
- Three fuels: Jet A and 2 blends of varying composition
- Corresponding ground test
- Also sampled commercial aircraft flights of opportunity in the national air space targeting advanced engines

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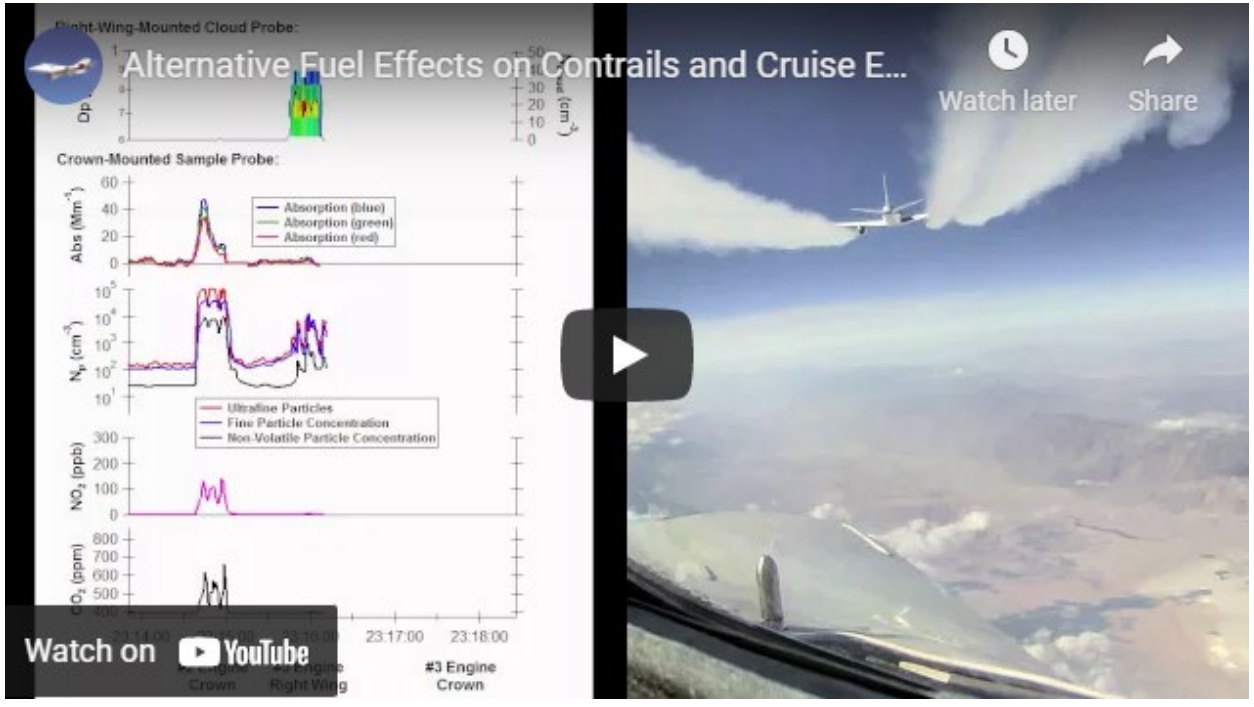
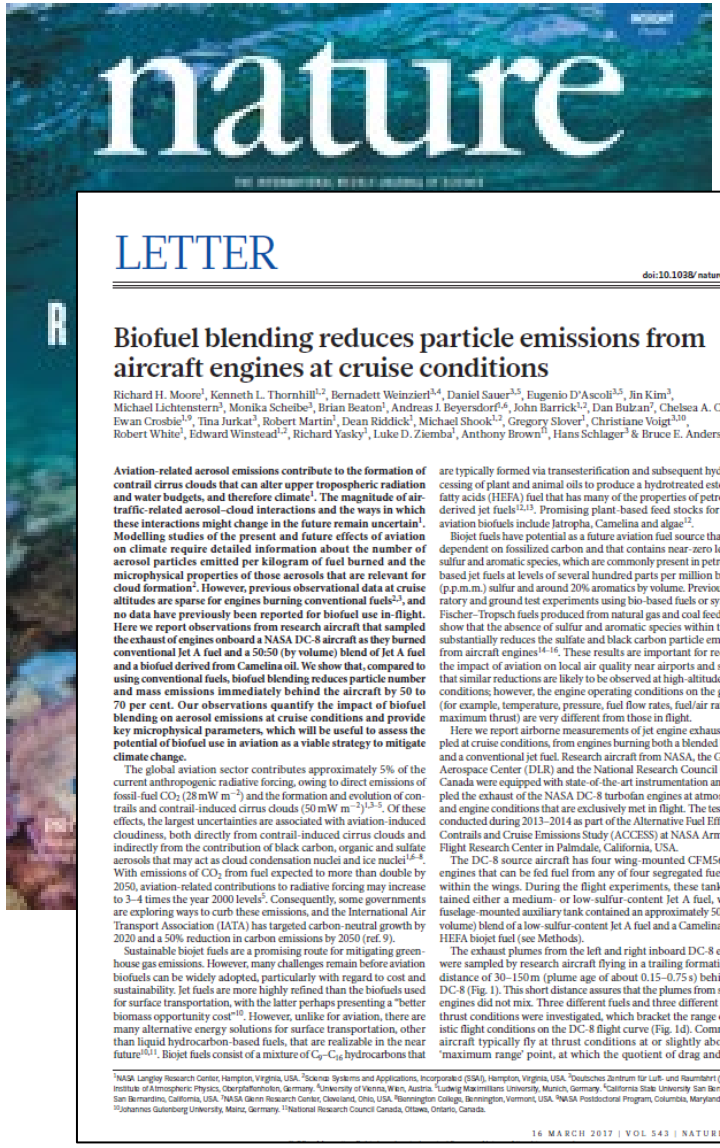
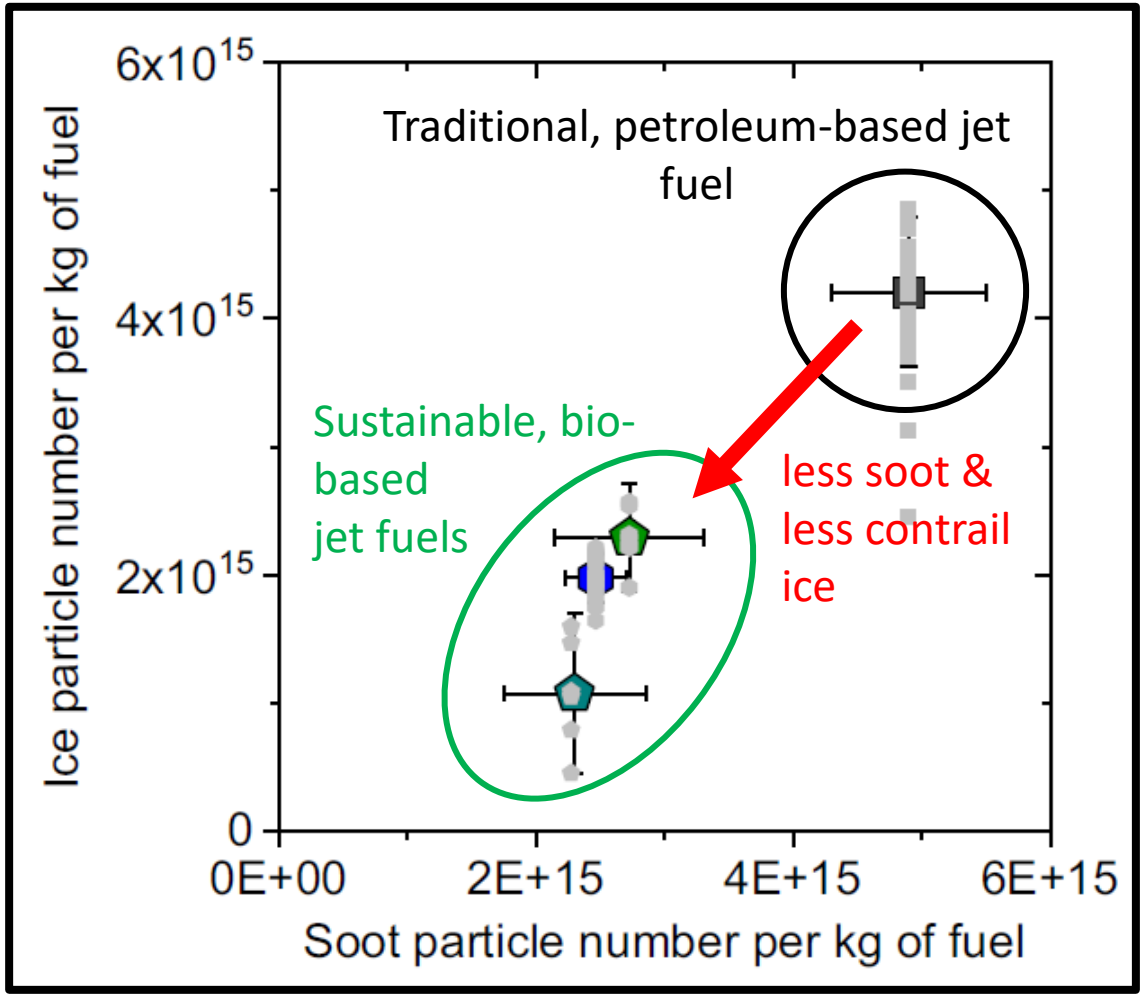
Videos of in-flight emissions sampling on YouTube



NASA Videos of ACCESS, ND-MAX Flight Projects:
https://youtu.be/ZMWXlUi68ng
https://youtu.be/CMU0b6CmGw0
https://youtu.be/vuZhkaJzSHE

Recent Flight Tests Demonstrate Strong Emissions & Contrail Reductions From 50:50 SAF Blends

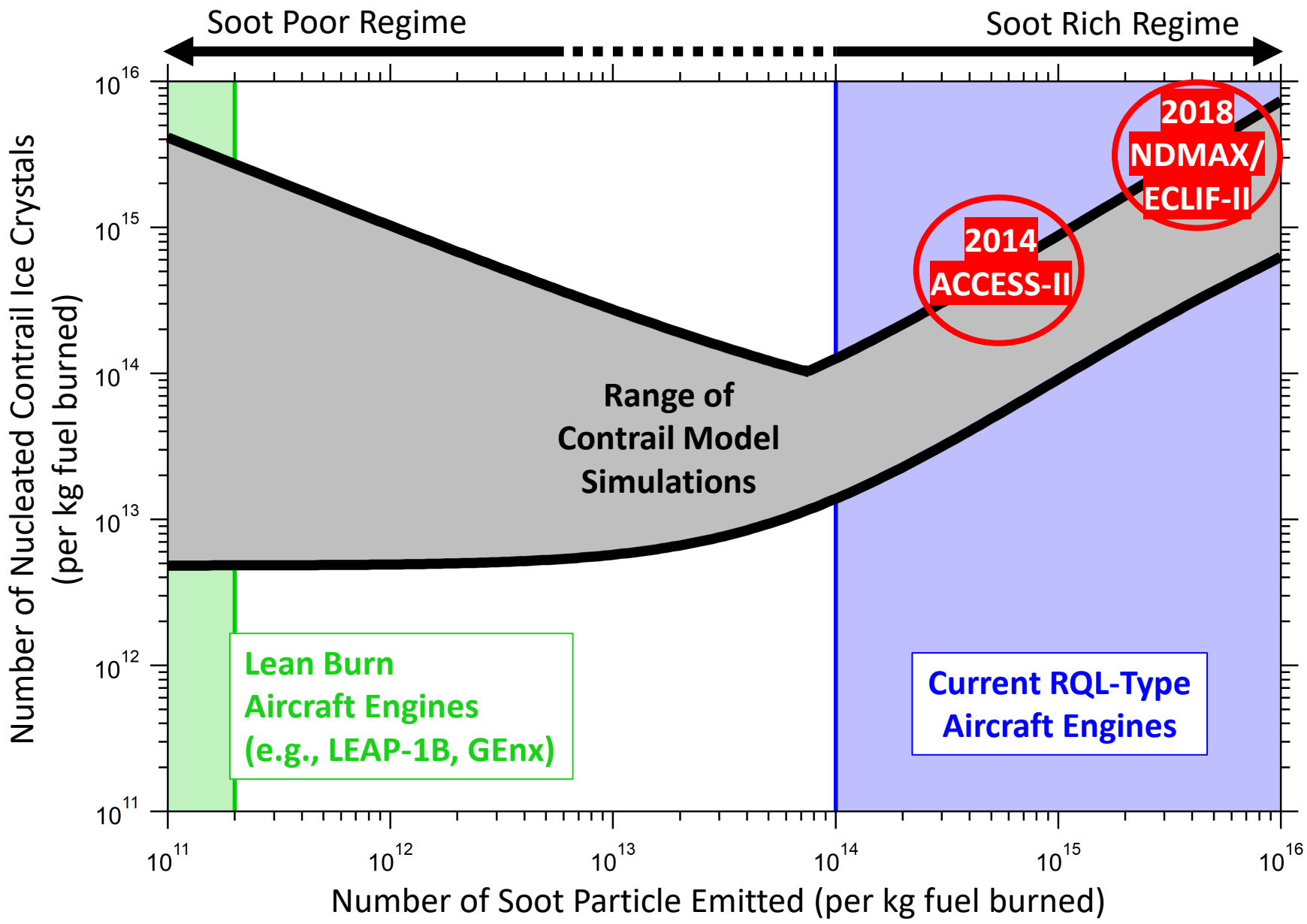




Moore, R.H. et al. (2017), *Nature*, https://www.nature.com/articles/nature21420

Voigt, C. et al. (2021), *Nature Comms. Earth & Environ.*, https://www.nature.com/articles/s43247-021-00174-y

But…These Past Tests Conducted Under "Soot-Rich" Conditions We Need to Understand The "Soot-Poor" Regime!



Need to understand engine particle emissions in the "soot-poor" regime in order to connect to contrail formation and climate impacts

Emissions reductions also beneficial for air quality

Figure adapted from Kärcher, *Nature Communications*, 2018.

Red circles show the approximate Number EIs observed during the 2014 ACCESS-II and 2018 ND-MAX/ECLIF-II flight test series.

Moore et al., Nature, 2017; Voigt et al., Nature Comms. Earth & Environ., 2021

ecoDemonstrator PROGRAM

NASA

2021-2022 NASA-Boeing-FAA ecoDemonstrator Emissions Ground Tests

October, 2021

Boeing Field, Seattle, Washington

September – October, 2022

Boeing Everett Delivery Center, Everett, WA

Leaving Langley

1st Night in Dayton, OH

Crazy Mountains Of Montana

Arrived at Boing Field

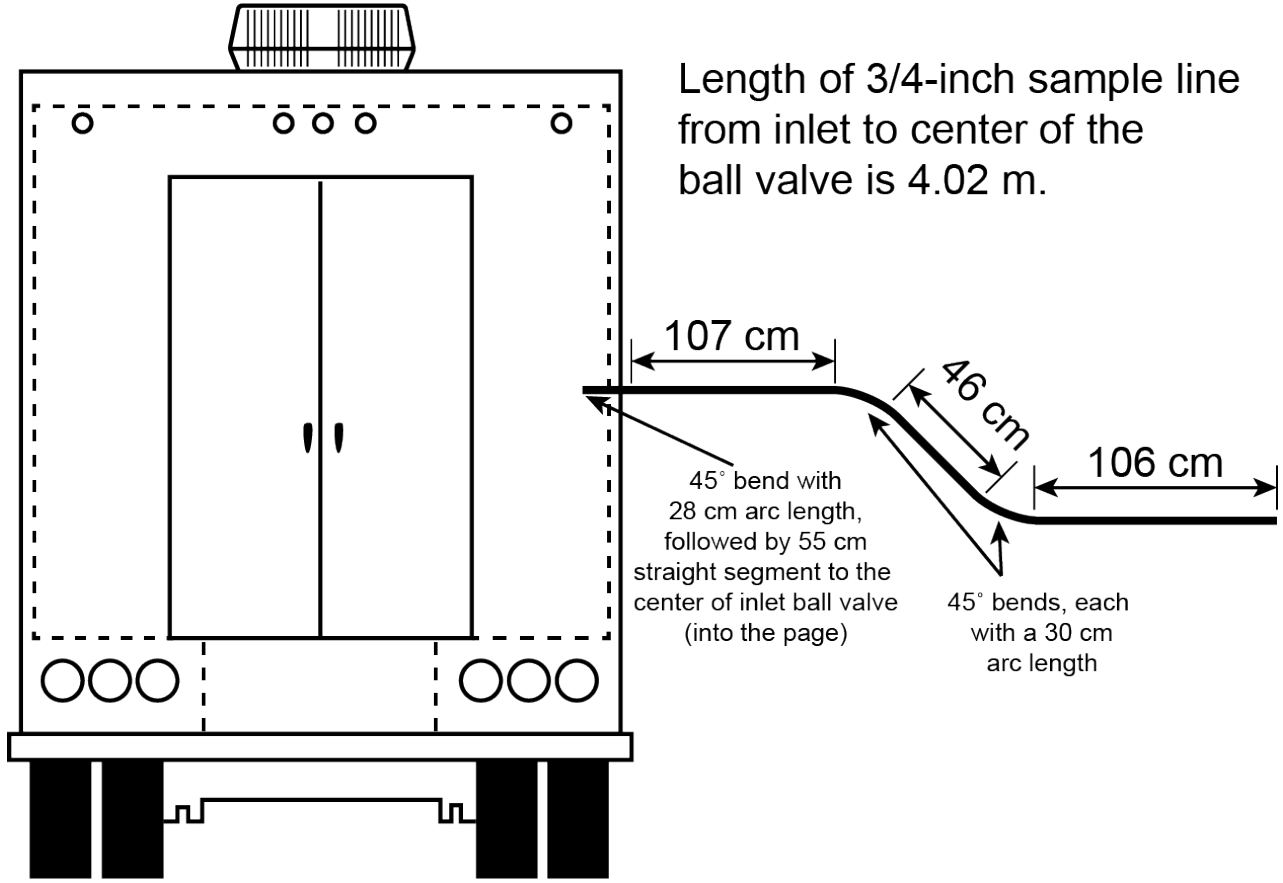
Madison, WI

Sunrise in North Dakota

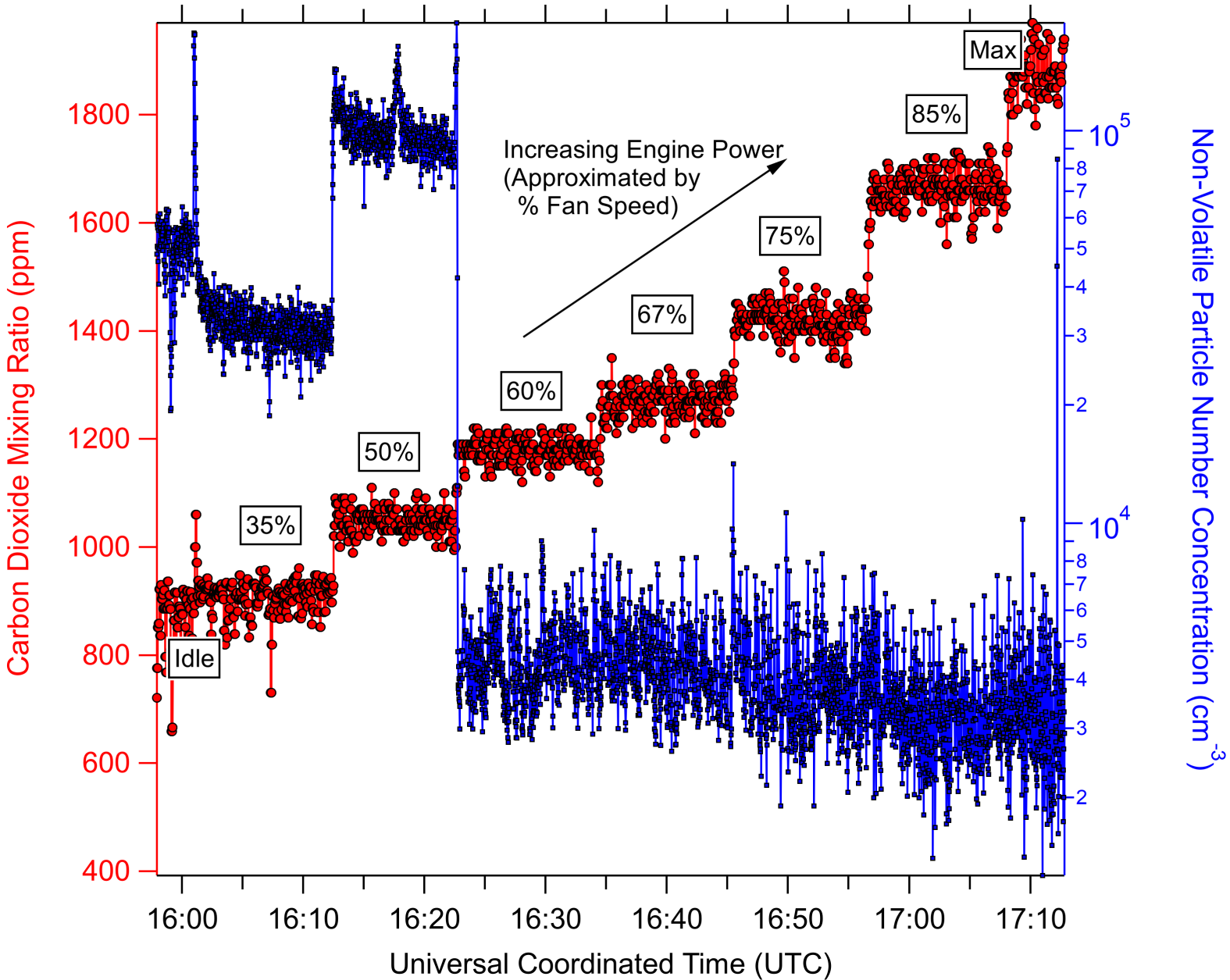
Photo Credit: Boeing / Paul Weatherman

Photo Credit: Boeing / Addison Salzman

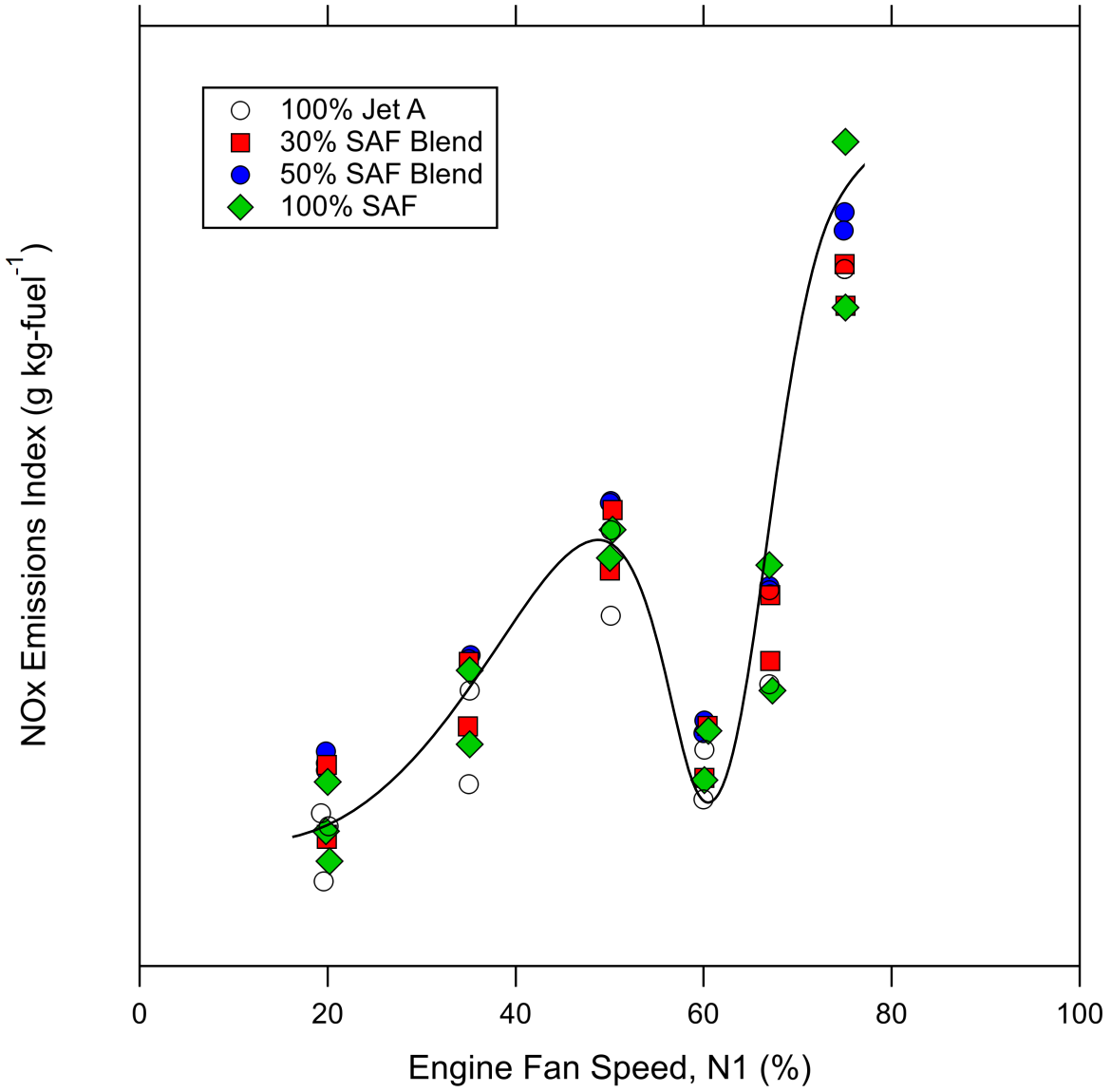
Short Sampling Line Reduces Particle Losses to Tube Walls!

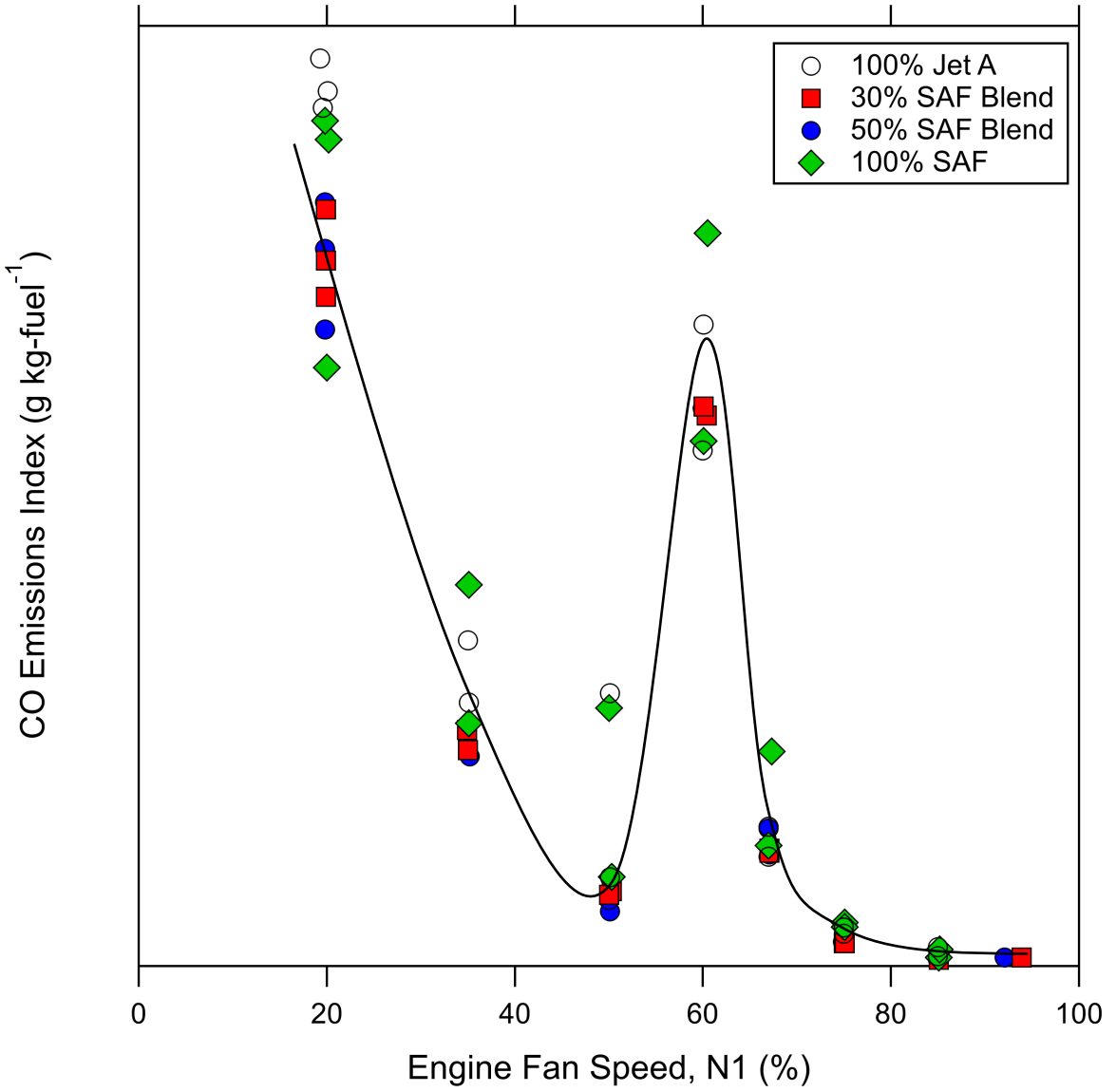


Test Matrix Sampled 8 Thrust Conditions Both in Ascending, Descending



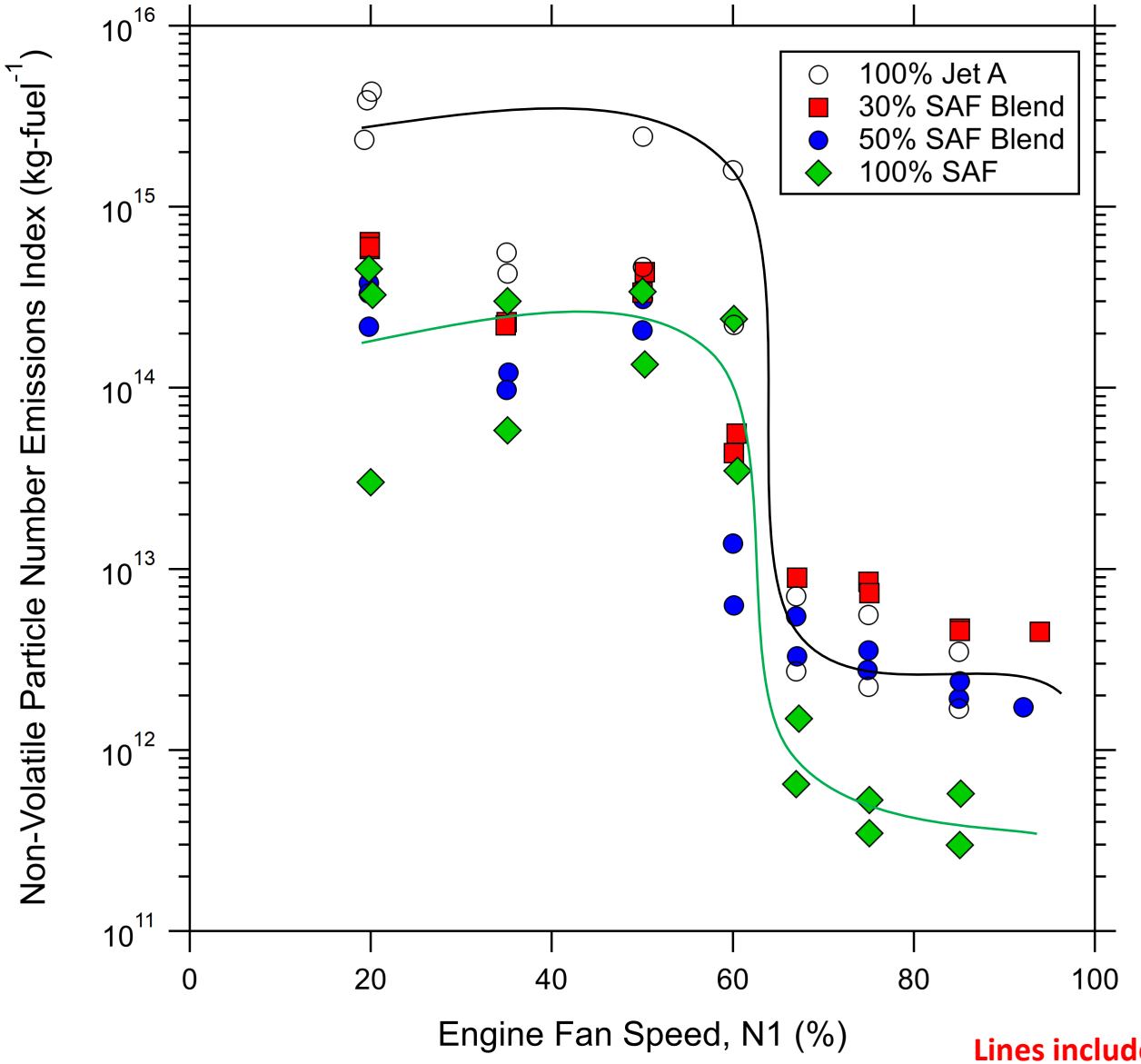
Trace Gas Emissions Indices Invariant With Fuel (as expected)

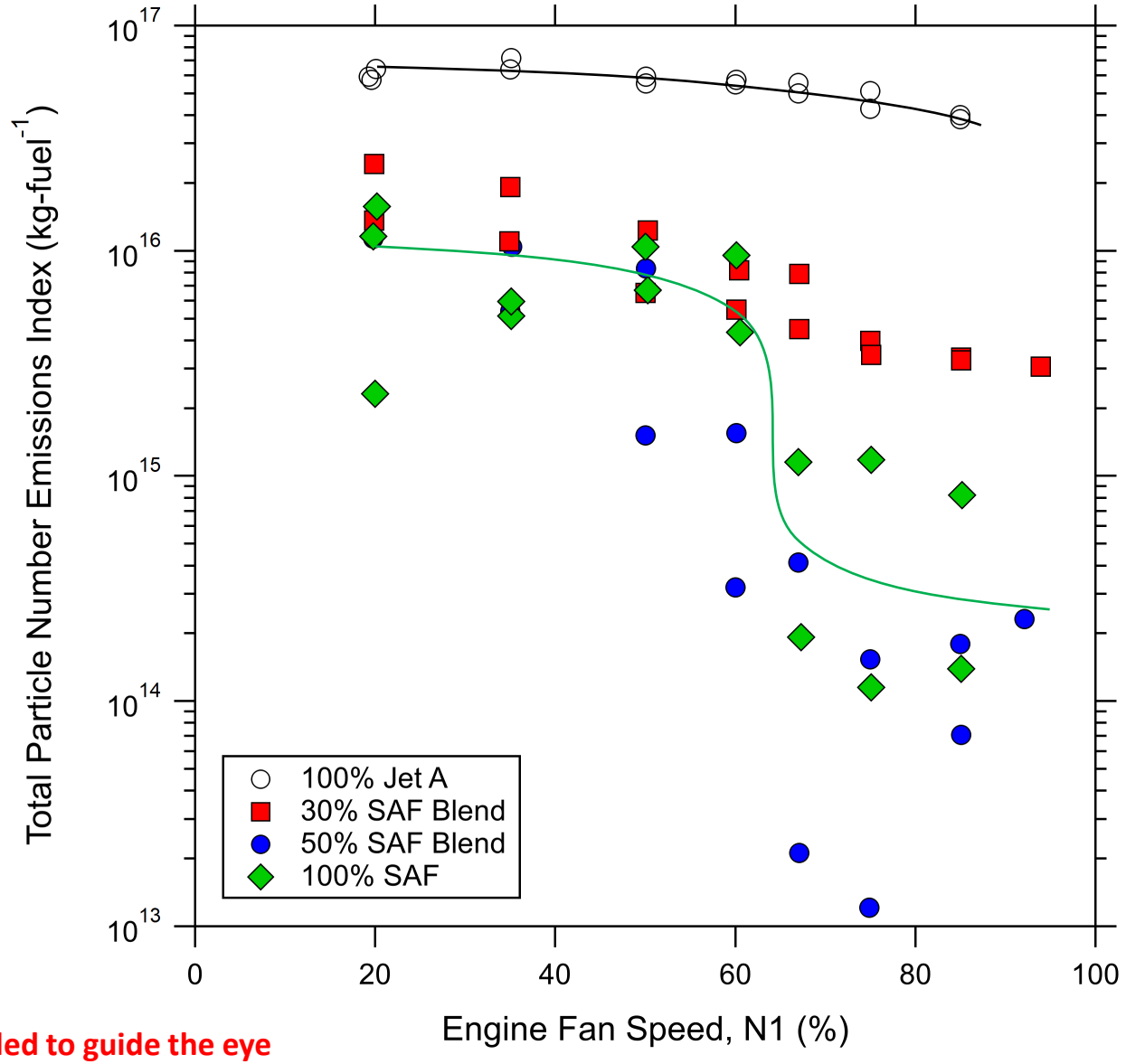




Lines included to guide the eye

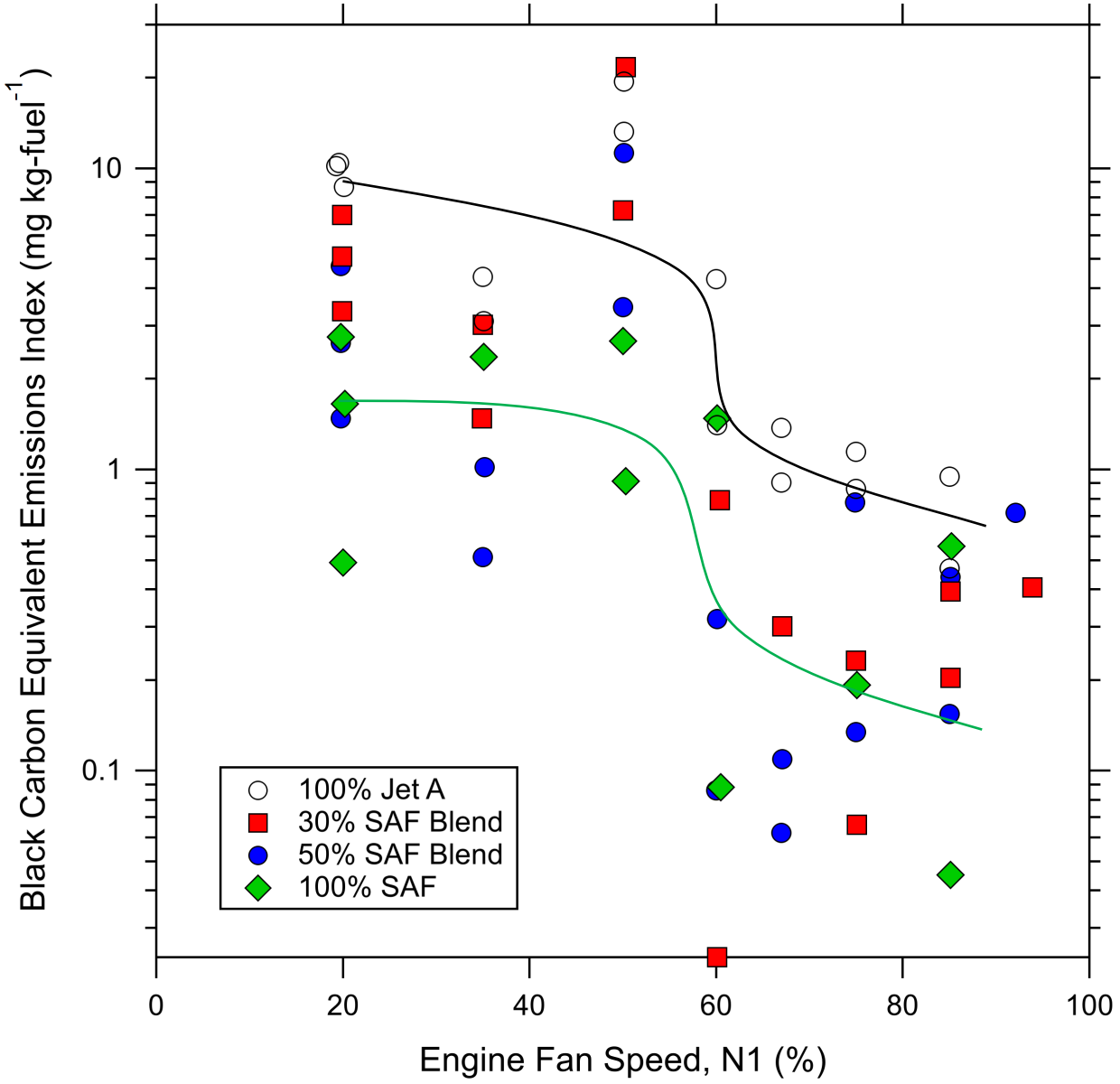
Significant Fuel Impacts on Non-Volatile and Total Particle Number





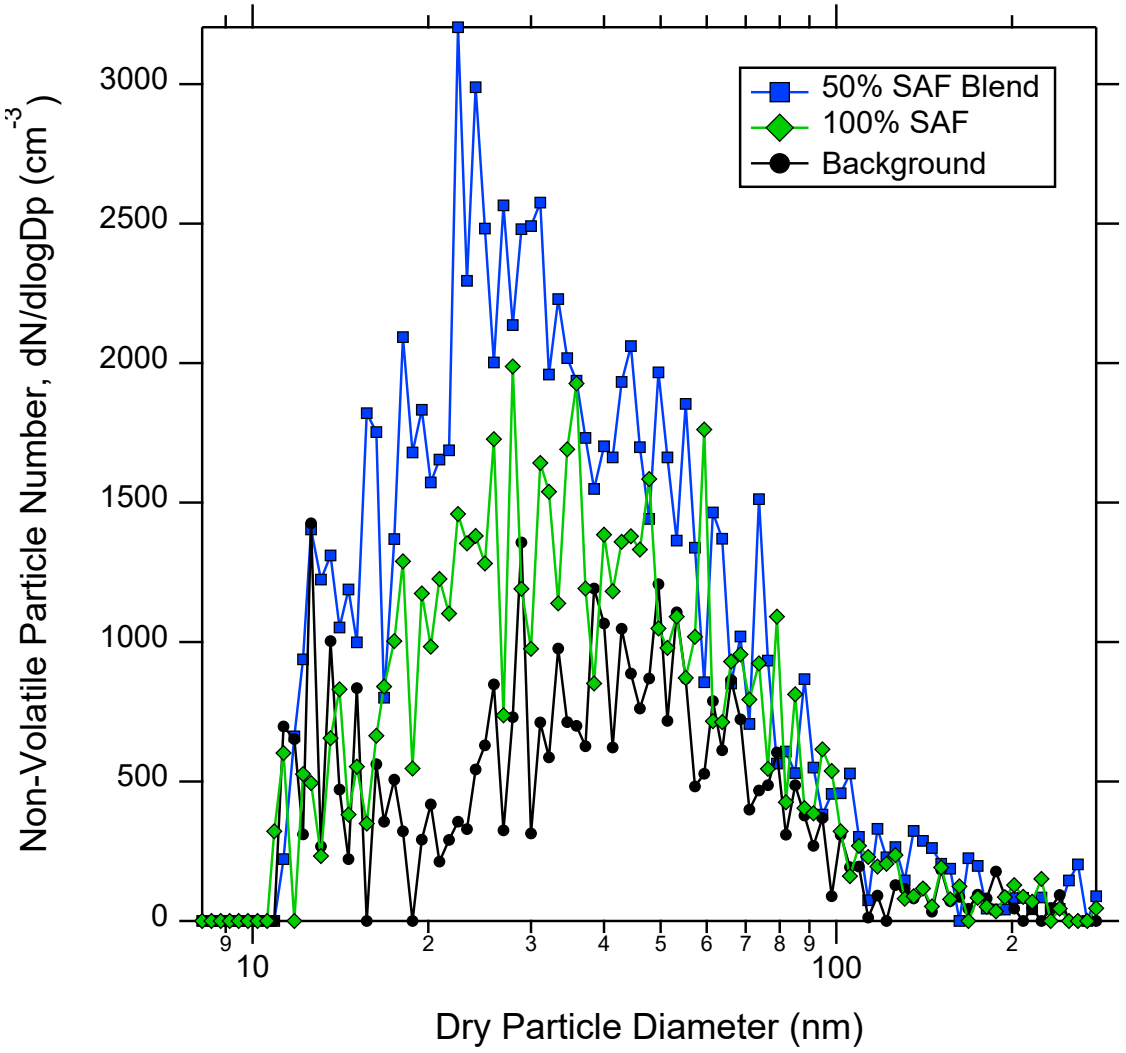
Lines included to guide the eye

Fuels Also Impact Black Carbon Mass; Although, Noisy Because Absorption-Based Mass Measurements Are Near Background Values



Lines included to guide the eye

Example Size Distributions at 85% Thrust Demonstrate The Challenge With Integrated Mass (Volume) Measurements Versus Number



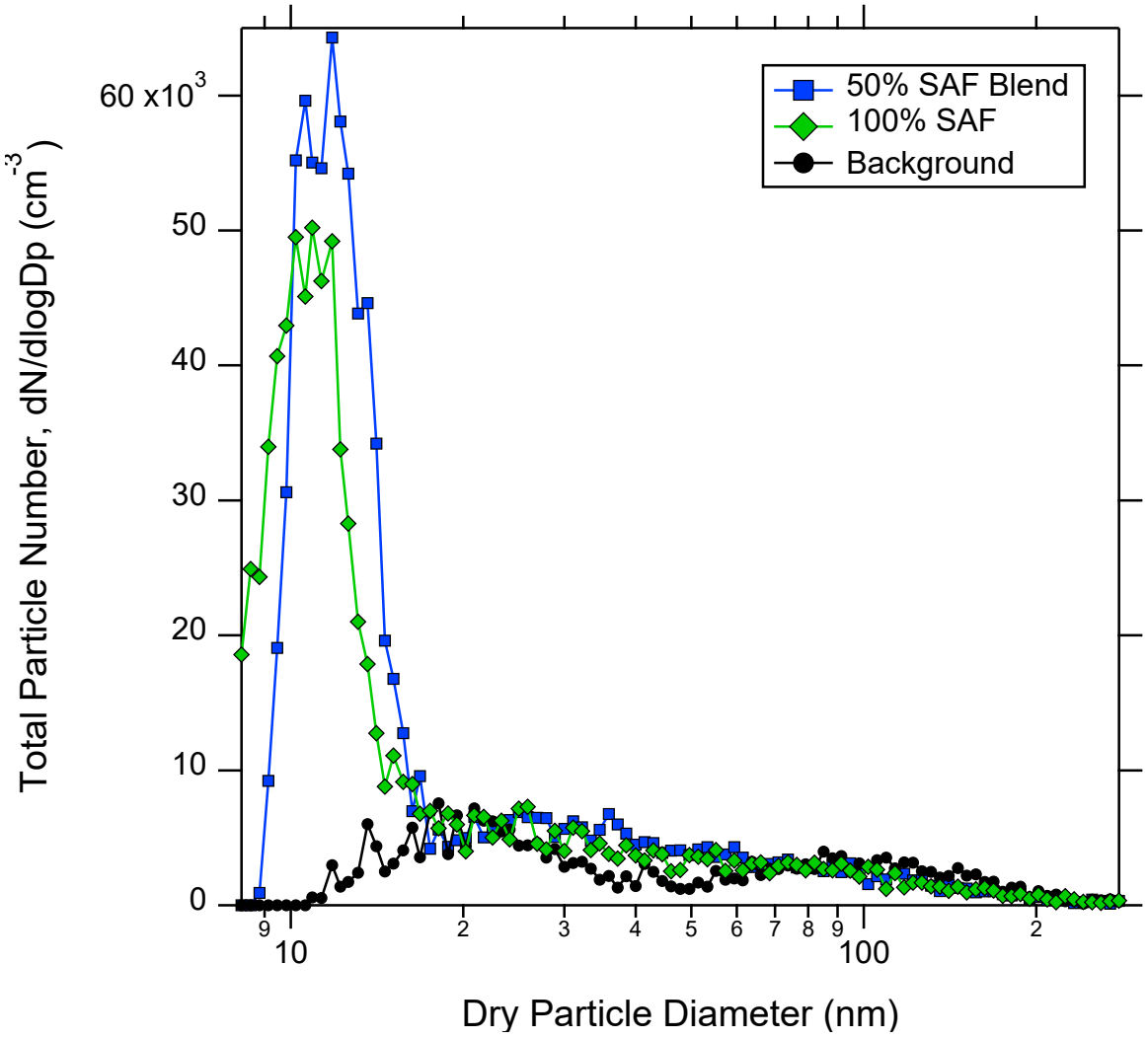


Photo Credit: Boeing / Paul Weatherman

eco Demonstrator PROGRAM

NASA

2022 Test Details:

- **Two Aircraft:**
  - Boeing 787-10 with GE Genx Engines
  - Boeing 777-200ER with Rolls-Royce Trent 800 Engines
- **Four Fuels:**
  - Jet A
  - Low-Sulfur Jet A
  - 50% SAF + 50% Low-Sulfur Jet A
  - SAF
- **4 Weeks at Boeing's Everett Delivery Center**
- **2 Costco-Sized Containers of Peanut M&Ms**

Lessons Learned, Gaps, and Future Opportunities

- Multi-decade, international, collaborative research effort to quantify SAF impacts on engine soot particle emissions
  - Ground tests in the 2000s (APEX 1-3 series and AAFEX 1-2 series),
  - Flight tests in the 2010s (ACCESS, ECLIF-I, and ECLIF-II/ND-MAX)
  - Future tests being planned for 2020s by NASA, DLR, and other international partners

- Adopting pure SAFs or SAF blends results in substantial soot particle number and mass emissions of 2-3x at cruise conditions that translate directly into contrail ice crystal reductions; larger reductions seen at ground idle conditions

- Past flight measurements have focused on 50:50 SAF blends to meet current ASTM specifications for fuel properties and fuel system compatibility with elastomeric seals. Need to measure emissions from burning pure SAF in flight.

- Past emissions characterization has focused on easily accessible engines (DC-8 CFM56-2's, ATRA IAE V2500's) that have soot particle emissions indices in the "soot-rich" regime. Need to study contrails in "soot-poor" regime.

- Boeing ecoDemonstrator Program is ideal for getting both of both worlds – advanced fuel + low-emitting engines